ISSN Print: 2394-7489
ISSN Online: 2394-7497
IJADS 2024; 10(2): 407-411

www.oraljournal.com
Received: 14-05-2024
Accepted: 16-06-2024

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Innovation horizons in orthognathic surgery: Embracing digital dynamics

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DOI: https://doi.org/10.22271/oral.2024.v10.i2f.1969

Abstract
Complex orthodontic cases often necessitate surgical jaw realignment or dentoalveolar segment repositioning when growth modification or camouflage is not viable. Contemporary tools like 3D imaging, intra-oral scanning, computer-assisted design (CAD) and manufacturing (CAM), and additive manufacturing have transformed orthognathic surgery through digital workflows. Virtual Surgical Planning and 3D printing enhance precision, safety, and patient satisfaction compared to conventional methods. Efficiency in time and cost, alongside technological advances, is highlighted, with a focus on educating surgical trainees. Effective management integrates pre-surgical orthodontics, surgery, and post-surgical phases, utilizing advancements in clinical imaging and manufacturing. Collaboration among orthodontists, oral surgeons, and technicians is crucial for optimal outcomes in occlusion planning and treatment.

Keywords: Orthognathic surgery, virtual surgical planning, precision, esthetics osteotomies

Introduction

Orthognathic surgery is a specialized field within oral and maxillofacial surgery dedicated to correcting abnormalities of the jaw and facial skeleton. The evolution of orthognathic surgery shares historical parallels with the management of traumatic facial injuries [1]. Early descriptions of mid face fractures by Rene Le Fort led to elective facial osteotomies in the mid-20th century, pioneered by surgeons like Norman Rowe, Paul Tessier, Hugo Obwegeser, and William Bell [2]. Advances in anesthetic techniques and rigid fixation in the 1980s improved surgical predictability. Distraction osteogenesis in the 1990s expanded surgical options for congenital and developmental facial skeletal differences [3]. Digital imaging and surgical planning in virtual environments further refined surgical precision, while CAD/CAM enabled customized cutting guides and implants, enhancing safety and efficiency in complex interventions [4]. Contemporary advances in orthognathic surgery include further advances in surgical planning, changes in coordinated orthodontic-surgical protocols, advanced distraction techniques, greater understanding of the changes in airway dynamics that accompany selected movements of the facial skeleton and expanding indications for patients with complex facial differences requiring simultaneous orthognathic surgery and free tissue transfer [5]. Classical surgical planning in orthognathic surgery required the use of cast dental models mounted on a semi-adjustable articulator to reproduce the relationship of the jaws to the cranial base. In severe orthodontic cases where growth modification or camouflage is inadequate, surgical realignment of jaws or repositioning of dentoalveolar segments becomes necessary [6]. Successful treatment integrates pre-surgical orthodontics, surgery, and post-surgical care. Advances in 3D imaging, intra-oral scanning, CAD/CAM, and additive manufacturing have revolutionized management.

Collaboration among orthodontists, surgeons, and technicians is critical. Traditionally, ideal occlusion was planned using 2D cephalometrics. Misaligned jaws cause difficulties in chewing, speaking, and breathing. For example, a severe underbite can hinder food consumption; leading to digestive issues [7].

An open bite may affect speech clarity, impacting social interactions and self-confidence. Orthognathic surgery improves eating, speaking, and breathing comfort through realignment of the jaws, supported by an interdisciplinary approach integrating orthodontics, radiology, and speech therapy. This holistic care model prioritizes overall patient well-being [8]. Surgery offers long-term benefits by reducing tooth wear, lowering TMJ disorder risks, and potentially improving sleep apnea. However, reliance on two-dimensional imaging like cephalometric radiographs limits understanding of complex anatomical relationships, potentially compromising surgical accuracy and outcomes due to human error and variability in practitioner skill [9]. The emergence of CAD/CAM technologies has revolutionized multiple fields, including healthcare [10]. Virtual surgical planning and 3D printing is natural progressions of these advancements, offering unparalleled precision and customization in orthognathic surgery. Ethical considerations, such as patient consent and data security, will also be addressed [11]. The introduction of Virtual Surgical Planning and 3D printing represents a revolutionary period in orthognathic surgery, heralding significant progress in surgical precision, effectiveness, and patient-centric results. This review highlights the potential of advanced technologies to improve surgical precision, reduce operating times, and enhance patient satisfaction, setting a new standard in orthognathic surgery. It aims to guide healthcare professionals and policymakers seeking to leverage these innovations for better clinical outcomes [12].

Discussion: Virtual Surgical Planning offers high accuracy and precision, as evidenced by studies such as Chen *et al.*'s systematic review, which highlighted its superior predictive capability over traditional methods [13]. Alkhayer *et al.* demonstrated that Virtual Surgical Planning can reduce error margins to less than 2 mm, significantly improving surgical outcomes [14]. Additionally, Virtual Surgical Planning provides substantial time-saving advantages by streamlining planning processes, cutting planning time by up to 30% compared to labor-intensive manual measurements and 2D imaging. Implementation requires specific software and hardware, typically including features like 3D visualization, real-time adjustments, and scenario simulations. Virtual Surgical Planning in orthognathic surgery requires high-performance computers with capable graphics cards for optimal operation [15]. Haptic technology enhances virtual surgical planning by providing tactile feedback, improving perception of on-screen occlusal contact. Digital occlusal wafers adjust for retention and material thickness before 3D printing, aiding in surgical replication using gypsum models mounted on an articulator with a facebow transfer [16]. These orthognathic wafers, made of acrylic, serve as intra-operative guides to position jaws post-osteotomy. Digital 3D surgical planning platforms for orthognathic surgery have seen increased use, leveraging improved image acquisition, software capabilities, Personal Computer processing power, and precise 3D printing for accurate surgical simulations, planning, outcome assessment, and patient communications [17]. Patient-specific surgical guides from 3D-Virtual Surgical Planning enhance intra-operative precision. Key tools include 3D scanners for detailed surgical site imaging and 3D printers for fabricating physical models and guides. Software features encompass soft tissue simulation, bone segmentation, and predictive analytics for postoperative results [18].

Leading systems like Dolphin Imaging and IPS Case Designer offer different strengths; Dolphin provides superior imaging but requires 17 windows, while IPS Case Designer offers greater user-friendliness with 14 windows [19]. Both ensure fast acquisition and consistent programming paths, with the choice influenced by user preferences and system compatibility. Virtual Surgical Planning is pivotal in achieving precise surgical outcomes, especially in condyle positioning. It exhibits the highest agreement between planned and actual condylar positions, minimizing errors and emphasizing the importance of anatomical variations in surgical strategies. With its high accuracy, efficiency, and flexibility, it's a ground breaking tool in orthognathic surgery, increasingly adopted for its effectiveness and benefits to surgeons and patients alike. 3D printing, or additive manufacturing, enables creating three-dimensional objects from digital models [20]. In orthognathic surgery, 3D printing has diverse applications such as surgical guides, anatomical models, and customized implants, enhancing surgical precision and predictability. Different 3D printing technologies serve distinct purposes in medical settings: Fused deposition modelling is cost-effective and accessible, suitable for less complex models [21]. Stereolithography offers exceptional resolution for intricate structures like vascular networks. Selective laser sintering creates robust models and surgical tools with detailed precision. Each technology has specific advantages and limitations, determining its suitability for orthognathic surgery and other medical uses. The choice of material in 3D printing for medical applications is a crucial consideration, as it directly impacts the functionality and safety of printed objects [22]. Common materials includes polylactic acid, which is biodegradable and safe for temporary implants or surgical guides. Resins, commonly used in stereolithography printing, offer exceptional detail but may be less durable compared to other options. Nylon is valued for its strength and durability in selective laser sintering printing, used for robust surgical tools and anatomical models.

3D printing in medical settings offers significant advantages [23]. Virtual Surgical Planning in orthognathic surgery enables precise, customized models essential for complex procedures, enhancing pre-operative visualization. Surgeons utilize patient-specific guides and implants, such as prebent plates, to optimize treatment outcomes. Efficient printing facilitates multiple copies once digital models are prepared, despite challenges like high setup costs, material expenses, and the need for expertise in sterilization. While Virtual Surgical Planning offers benefits in precision and efficiency, meticulous planning remains critical [24]. Comparative studies show Virtual Surgical Planning's superiority over Traditional Surgical Planning in accurately predicting soft tissue changes, reducing surgical time, and improving outcomes in collaborative environments. Initial adoption of Virtual Surgical Planning may prolong the planning phase, especially for those less familiar with digital technologies. Virtual Surgical Planning in orthognathic surgery demonstrates superior precision in soft tissue changes, with mean differences below 1.50 mm vertically and horizontally, compared to over 2.00 mm with traditional methods [25]. However, consensus on optimal 3D prediction models remains unresolved. Integrating 3D models could enhance soft tissue estimation accuracy, highlighting Virtual Surgical Planning's potential. Both Virtual Surgical Planning and Traditional Surgical Planning show comparable accuracy in hard tissue alignment in the sagittal plane, but empirical research is needed to validate and refine Virtual Surgical Planning prediction models. Utilizing the nasal notch of the maxilla as a stable reference point, 3D printing-assisted approaches enhance surgical precision by minimizing errors associated with traditional methods. Modern orthognathic surgery employs 3D virtual simulations and 2D cephalometric analyses for precise preoperative planning, mitigating inaccuracies in traditional techniques.

Despite higher costs and specialized training, 3D printing enables patient-specific guides and plates, improving outcomes when combined with Virtual Surgical Planning. Psychological support and adaptation to facial changes post-surgery are increasingly prioritized in orthognathic surgery, reflecting a shift towards holistic patient care [26]. Studies like Schneider *et al*.'s prospective trial highlight Virtual Surgical Planning's superior accuracy and reduced operation duration, despite higher initial planning costs. Virtual methodologies are poised to potentially replace traditional approaches as they become more cost-effective [27]. Resnick *et al*.'s retrospective study and Park *et al*.'s research in Korea underscore significant time savings with Virtual Surgical Planning, particularly in complex surgeries, though the financial benefits remain less clear [28]. Overall, these findings suggest a transformative impact of 3D technologies on the financial landscape of orthognathic surgery. Advanced orthognathic surgery technologies, such as Virtual Surgical Planning and 3D printing, offer significant time savings and accuracy improvements despite higher initial costs compared to traditional 2D methods. When considering broader impacts like enhanced quality of life and reduced operation times, the economic case for 3D technologies becomes compelling. Future analysis should focus on diverse case studies and long-term financial implications to fully grasp their cost dynamics as technology matures and scales. Addressing research gaps through rigorous, large-scale randomized controlled trials will be crucial for understanding and optimizing the potential of these technologies in orthognathic surgery [29]. There is a pressing need to delve deeper into the ethical considerations and to develop frameworks that ensure the responsible adoption of these technologies. Moreover, studies should explore the potential of these technologies in medical education, particularly in enhancing the training experience for surgical trainees and junior surgeons. Furthermore, research should focus on the continual advancements in Virtual Surgical Planning and 3D printing technologies, including exploring new materials and techniques that can further enhance the accuracy and efficiency of surgical planning and execution [30]. Orthognathic surgery has been a mainstay of craniomaxillofacial surgical treatment for over a century. Midface and mandibular osteotomies correct complex dysmorphology, improving occlusion, facial aesthetics, and managing airway obstruction. Planning includes sagittal and vertical jaw positioning relative to the cranial base, with osteotomies like Le Fort and Bilateral Sagittal Split Osteotomy adjusted across multiple planes. The 'maxilla-first' approach, endorsed for accuracy and reduced fixation risk, guides surgical alignment using a rigid point registration algorithm. Clinical exams and patient history guide surgical decisions based on occlusion, function, and aesthetics [31]. Digital radiographs streamline analysis, while intra-oral scanning provides precise digital impressions of the maxilla and mandible. Creating a 3D model for orthognathic Virtual Surgical Planning involves obtaining Computed Tomography or Cone Beam Computed Tomography scans post pre-surgical orthodontic treatment. These scans are imported as 2D DICOM data for volume rendering and segmentation of maxilla and mandible. High-resolution intra-oral scans supplement Cone Beam Computed Tomography for detailed dental imaging. The integrated virtual patient model supports precise surgical planning using cephalometric references like the Frankfort horizontal plane. In bimaxillary planning, this plane guides anteroposterior assessment and maxillary canting determination. Virtual osteotomies are planned using intersection points on the model, adjusting cutting planes to align with surgical goals and avoid critical structures [32]. Cone-beam Computed Tomography offers convenience, minimal radiation exposure, and detailed guidance during procedures such as bilateral sagittal split osteotomy to safeguard against nerve damage and paresthesia. Computer-Assisted Surgery System offers advantages like visualizing interferences and dental roots, and facilitates choosing between segmental and single-piece Lefort options for ideal occlusion in single-jaw cases [33]. In double jaw surgery, both maxilla and mandible movements are coordinated relative to each other. Traditional model surgery using semi-adjustable articulators and face bow transfers was prone to errors and lacked full perspective on facial and skeletal relationships. Computer Assisted Surgery System eliminates these issues, streamlining planning through online collaboration between surgeons and engineers. Segmental Lefort surgeries, enhancing transverse expansion and bite closure, also benefit significantly from digital planning capabilities. Computer Assisted Surgery System enables visualization of root distances and facilitates cutting guide fabrication for segmental osteotomies. 3D-printed palatal inserts maintain maxillary transverse expansion without cumbersome final splints, reducing operating time. It allows visualization and planning of atypical osteotomies, opening new surgical options for challenging cases [34]. Guided surgery and custom fixation techniques now support procedures like intra-oral inverted L osteotomy, C osteotomy, Z osteotomy, and total mandibular subapical osteotomy. Technique-sensitive osteotomies like inverted L, C, Z, and total mandibular subapical osteotomies can greatly improve patient outcomes [35]. Advances allow for bone grafting from the maxilla and mandible, reducing the need for separate donor sites like the iliac crest. Custom guides and fixation can be costly and should be reserved for complex cases. Modern digital workups enhance surgical accuracy and speed without compromising surgical principles. More specifically, historical planning was based largely upon the occlusion alone, rather than a comprehensive understanding of the changes in bone position and interferences that accompany changes in the dentate jaws (i.e., pitch, yaw, and roll). Higher fidelity images capture modalities and a greater understanding of the complexities of movements as rendered in a three-dimensional virtual surgical environment have allowed surgeons to more effectively and precisely address myriad skeletal deformities, with decreased operating time and hospital stays [36]. Recent advancements in orthognathic surgery include surgery-first and surgery-only approaches, alongside the use of clear aligners instead of braces, aiming to streamline treatment and minimize aesthetic impacts from presurgical orthodontics. Traditional planning involves presurgical orthodontic "decompensation" to align dental deformities with skeletal discrepancies, followed by postsurgical adjustments for final dental alignment [37]. Ebkar *et al*. endorse a surgery-first approach using computer-assisted planning, integrating surgical and orthodontic movements in a virtual 3D model to align splints with desired outcomes. However, patients in their study wore passive maxillary/mandibular splints post-planning to stabilize teeth positions. Initial preparation for surgery-first cases necessitates precise analysis of current and projected occlusion and facial aesthetics. The surgery-first approach has shown promising benefits, including a potential reduction in treatment time by up to 8 months compared to traditional methods [38]. Studies indicate comparable stability and surgical outcomes, fostering increased adoption among clinicians. Initially used predominantly for class III patients, its application is expanding to include class II malocclusions, craniofacial differences, and facial asymmetry cases, reflecting ongoing innovation in orthognathic surgery practices [39]. A recent study by Choi *et al*. has demonstrated through the use of Artificial Intelligence assessing cephalometric measurements that relapse rates are similar in both orthodontics first and surgery first approaches [40]. Moreover, they have been able to show that despite the difficulties in both the assessment and treatment of patients with facial asymmetries, using the surgery first model, they can achieve predictable results. Orthognathic surgery is a specialized branch of oral and maxillofacial surgery that focuses on correcting irregularities of the jaw and facial skeleton.

One of the most compelling reasons for the importance of orthognathic surgery lies in its ability to dramatically improve a patient's quality of life through enhanced functionality [41].

Limitations and future directions Literature on Virtual Surgical Planning and 3D printing in orthognathic surgery reveals several limitations: small sample sizes potentially introducing bias, a scarcity of randomized controlled trials, and mostly retrospective studies prone to selection bias. Methodological variations across studies hinder direct comparison of results, with some focusing narrowly on time efficiency or accuracy, neglecting broader factors like patient satisfaction and economic implications. These gaps underscore the need for comprehensive research addressing ethical dimensions such as patient consent and data security. Long-term outcomes and economic analyses are also underexplored, necessitating further studies to assess impacts on patient quality of life, satisfaction, and the cost-effectiveness of these technologies over extended periods [42].

Conclusion

Digital tools such as 3D imaging, virtual surgical planning, and intra operative navigation enhance surgical precision, leading to better outcomes and reduced complications. They allow for personalized treatment plans that improve clinical results and patient satisfaction. Despite initial costs, these innovations streamline workflows, shorten operating times, and potentially lower healthcare expenses by preventing complications. Virtual simulations and augmented reality aid in surgeon training and patient education, promoting informed decision-making and confident surgical approaches. Embracing digital advancements in orthognathic surgery offers significant benefits, promising safer, more precise, and personalized procedures that elevate standards of care. However, challenges persist in cost, technology adoption, and the need for comprehensive research. The lack of large-scale randomized controlled trials and fragmented studies underscore the need for rigorous research in this evolving field. Ethical and economic considerations of integrating these technologies into healthcare warrant further exploration to ensure responsible and sustainable use. As the medical community navigates this technological era, a balanced approach is crucial, embracing innovation while critically assessing potential drawbacks. Collaboration across disciplines will be essential in optimizing the utilization of Virtual Surgical Planning and 3D printing for advancing patient care.

Financial support and sponsorship: Nil

Conflicts of interest: There are no conflicts of interest

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How to Cite This Article
Wadhawan R, Debnath M, Singh A, Kumar S, Kumar S, Gurjar SS. Innovation horizons in orthognathic surgery: Embracing digital dynamics. International Journal of Applied Dental Sciences. 2024; 10(2): 407-411.